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Multispectral Thermal Imager (MTI)
Satellite Imaging Operations and Performance

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Abstract

MTI is a comprehensive R&D project, featuring a single satellite in sun-synchronous orbit designed to collect radiometrically accurate images of instrumented ground sites in 15 spectral bands ranging from visible to long-wave infrared. The satellite was launched from Vandenberg Air Force Base on March 12, 2000 aboard an Orbital Sciences Corporation Taurus rocket. After launch, the operations team completed a 3-month turn-on, checkout and alignment procedure, and declared the satellite ready for its R&D mission on June 14, 2000. The satellite has collected over 1850 images in support of its research mission. This paper presents a brief satellite overview and documents satellite autonomous control, operations, and performance.

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Introduction

This paper will introduce readers to the National Nuclear Security Administration's (NNSA) Multispectral Thermal Imager (MTI) project with emphasis on the satellite's imaging operations and performance. MTI is a Research and Development (R&D) project, sponsored by the NNSA's Office of Nonproliferation and National Security and executed by Sandia National Laboratories, Los Alamos National Laboratory and Savannah River Technology Center. Other government participants include the Air Force Research Laboratory, the National Institute of Standards and Technology and the Air Force Space Test Program, which funded and managed the launch. Major industry participants include Ball Aerospace, Raytheon Optical Systems, Raytheon Infrared Center of Excellence and TRW. Over fifty government, private and academic organizations were involved in the development.

MTI was placed into orbit by the fifth launch of the Taurus Launch Vehicle (T5) built by Orbital Sciences Corporation. In addition to its primary imaging payload, MTI carries an STP sponsored Hard X-Ray Spectrometer (HXRS) experiment.

NNSA's primary objective for MTI is to develop and evaluate advanced multispectral and thermal imaging, image processing and associated technologies for nonproliferation treaty monitoring and other defense and civilian applications. The developed technology will help address in the future the threat of proliferation of weapons of mass destruction. The MTI satellite, carrying an advanced multispectral pushbroom imaging payload, was launched on March 12, 2000 from Vandenberg Air Force Base aboard an Orbital Sciences Corporation Taurus launch vehicle and is now one year into its 3-year mission goal.

The satellite periodically records images of instrumented government, industrial and natural sites in 15 spectral bands ranging from visible to long-wave infrared with very accurate radiometry. These bands provide a broad range of data on surface temperatures, materials, water quality and vegetation stress. They also provided information needed to characterize and correct for the intervening atmosphere (column water vapor and aerosol content) and to detect subvisual clouds. The combination of spectral bands, accurate radiometry (3% in reflective bands and 1% in thermal emissive bands) and good spatial resolution (20 meters in the midwave to longwave IR and 5 meter in the visible) make MTI unique among current and planned space-based imaging systems. Site instrumentation provides investigators with simultaneous ground truth needed to analyze and validate the technology. Specific mission goals are:

- Verify achievement of spatial, radiometric and other performance goals
- Verify ability to characterize and correct for the intervening atmosphere
- Verify achievement of thermometric performance goal (1 Kelvin for known emissivities)
- Demonstrate utility and develop algorithms needed to detect and characterize proliferant facilities from their spatial-spectral-temporal signatures
- Support Department of Defense (DoD) experimentation and research
- Support climate, environmental and other civil experimentation and research

To ensure a broad range of defense and civil applications are addressed in addition to treaty monitoring, NNSA has formed an MTI users group (MUG), which serves as a vehicle for DoD and civilian experimenters to submit requests for imagery needed for their research. Membership is open to U.S. government and government-sponsored investigators wishing to conduct research in the national interest. The MUG currently has over 100 members from over 40 government organizations.

In addition to the primary sensor, the MTI satellite carries a High energy X-Ray Spectrometer (HXRS) sponsored by the National Oceanic Atmospheric Administration (NOAA), with additional funding from the Astronomical Institute Academy of Sciences of the Czech Republic, and built by Space Devices, Ltd. of the Czech Republic. HXRS is designed to record a rare species of solar flare associated with high-energy proton storms known to damage satellites and capable of endangering astronauts. From HXRS, NOAA hopes to obtain data needed to design systems capable of forecasting such storms. The HXRS payload was turned on 3 days after launch and has been collecting data since then.

The T5 countdown and launch were picture perfect. Insertion parameters were will within specified limits.

	Req.	Actual
Injection Aspe	575 ±10 km	584 km
Opposite Apse	575 ±50 km	621 km
Orbit Inclination	97.47° ±0.15°	97.40°
Solar Beta Angle	+15° ±3.75°	13.37°

Table 1 Orbit insertion parameters

System Overview

MTI's overall system architecture, multispectral pushbroom imaging sensor payload and other mission details are described in previous papers.[1,2,3,4,5] As an overview, the system includes a single satellite in sun-synchronous orbit, a store-and-forward communications architecture with a ground station and operations center located at Sandia National Laboratories and a Data Processing and Analysis Center (DPAC) located at Los Alamos National Laboratory.

The primary payload sensor features a 36 cm off-axis telescope, cryogenically cooled focal plane with 15 linear spectral-sensitive detector arrays, built-in calibration sources and mechanisms, supporting structure, and associated readout and control electronics. The entire satellite with primary and secondary payloads and supporting spacecraft bus weighs just over 1300 lbm. In its stowed configuration, it was roughly cylindrical in shape, 53 in. in diameter and 100 in. in length. The satellite carries no propellant; therefore, its orbit altitude is slowly decaying and its nominal 1:00 A.M. / 1:00 P.M. sun-synchronous orbit plane is slowly drifting.

When not imaging, the satellite is normally oriented with solar panels facing the sun, and the optical system pointed away from the sun. This orientation, referred to as standby mode, provides the payload with a stable thermal environment between images and optimum orientation for battery charging. To image, the satellite executes attitude maneuvers required to point a control frame on the satellite to a point on the earth and then sweeps the projection of the push broom imaging sensor across the target center. For a nominal 12x12 km image, each band collects data for a total of 1.8 seconds. The time required to collect the entire image (from first band turn-on to last band turn-off) is approximately 4 seconds. After recording an image, the satellite executes another attitude maneuver to return itself to standby-mode orientation. In addition to terrestrial sites, the satellite images celestial objects and cold space for vicarious calibration and focus checks.

Figure 1 Moon image taken by MTI Oct. 2000

Between ground contacts, spaced up to 12 hours apart, the satellite autonomously collects, compresses and stores up to five 2-look, 15-band image sequences together with housekeeping data. This is a 66% increase over the project requirements before launch. Ground contacts are established via three communication links as the satellite comes in view of the ground station:

(1) 2 kb/s real-time downlink for transmitting current status and state-of-health data
(2) 2 kb/s command uplink
(3) 8 mb/s mission data downlink

An image sequence is defined as 2 images of a given site taken in all bands taken from two different angles –one near nadir and one at 50 to 55 degrees off nadir.

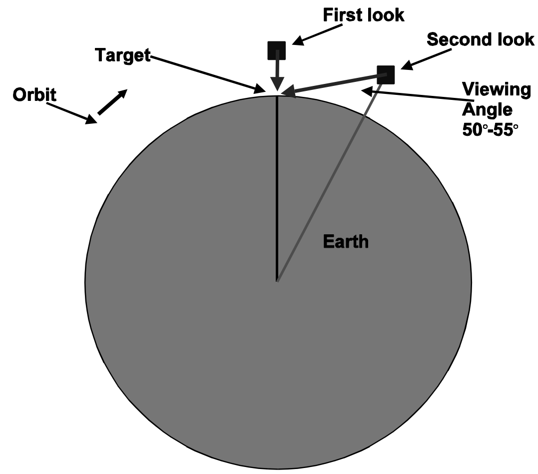

Figure 2 2-look image sequence

Nadir images nominally cover 12x12 km, and the satellite normally images sites located up to ±20 degrees off of its ground track (approximately ±200 km on the ground). Revisit time is nominally about 7 days; however, this varies as the satellite's altitude drops.

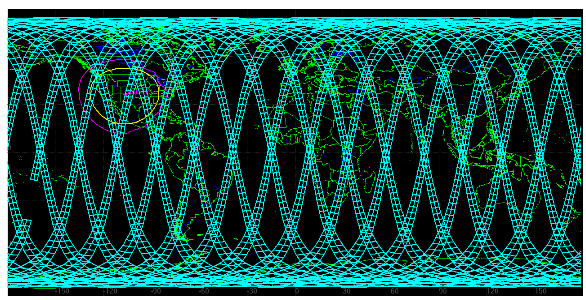

Figure 3 Representative image opportunity for one day

At the beginning of each ground contact, the satellite transmits current status and state-of-health data via the real-time downlink. These data are checked against a ground station database in near real-time, and depending upon the outcome of that check, the ground station then automatically commands the satellite to dump mission and housekeeping data stored in its solid state recorder via the mission data downlink. While the satellite is dumping stored data, the ground station automatically uploads autonomous procedures to be executed during the next 12 hours, which are stored in the satellite's command queue. Figure 2 shows a representative days worth of satellite imaging opportunities over the earth.

Post Launch Operations

Immediately following separation from the launch vehicle, the onboard separation timer began executing its preprogrammed turn-on sequence. While out of view from any ground station, 100 seconds after separation the satellite deployed the four solar panels by enabling the power bus that provides power to the solar array deployment mechanisms. Running off of battery power at separation +200 seconds the +X and -X solar array latches, wax actuators, began heating up. From test data the deployment of the solar panels was expected to take from 60-90 seconds from latch turn on. The heaters in the latches were turned-off 200 seconds after latch turn-on. At separation +500 seconds, the same sequence was executed to deploy the +Y and -Y solar panels. Less than 100 seconds after completing solar panel deployment the satellite entered sunlight for the first time.

The next action initiated by the separation timer was to orient the attitude of the satellite such that the GaAs solar arrays were pointing at the sun. This was accomplished by enabling the power bus that provides power to the attitude control components and turning on the attitude control processor (ACP), and the three reaction wheels on the satellite. After booting, the ACP enters an acquire sun state where it uses its fourteen coarse sun sensors to determine the direction of the sun. Using the reaction wheels to compensate for any residual angular momentum from tip-off torques, the ACP then maneuvered the satellite's attitude to point the solar panels at the sun.

The satellite was launched with components on the essential power bus already powered up. Thus once the solar arrays were facing the sun, the power control unit (PCU) began to control the battery charge using its direct energy transfer system in preparation for satellite entry into eclipse. During the sunlight portion of the orbit, energy is transferred from the solar array to the power control unit and then to the battery via a low impedance wire harness. The control section of the PCU determines how many solar array circuits are connected to the essential bus (EB) while charging the battery. This decision is based upon standard voltage/temperature (V/T) characteristics for the 40-amp-hour nickel-hydrogen battery. The battery provides power during eclipse and peak load conditions.

Power system fault control functions are also on the essential power bus inside the PCU. The PCU continuously monitors four different power busses for different pre-defined faults. In the event of current faults, the PCU will open appropriate power bus switches. This action actually occurred after two months on-orbit when a short circuit developed either in the solid state recorder c-side (SSR-C) or its power cable. Having sensed over 35 amps on the combined payload and non-essential bus, the PCU opened the power relays to the two busses as it was designed to do. After the MTI operations team isolated the SSR-C component, the the payload recorder interface was reprogrammed to store all data packets into the d-side (SSR-D) of the mass storage unit. Though SSR-C failed the mission has continued with no impact to requirements.[1]

The PCU also monitors the system for undervoltage, battery over pressure, battery over temperature, and battery cell voltage imbalance faults. MTI has experienced three undervoltage situations since launch, which are described in Reference 2. Upon detecting such faults, the PCU load sheds components not needed for survival and the ACP configures the satellite into a stable attitude for battery recharging.

The final action of the separation timer was to configure the satellite to begin transmitting real-time state-of-health (RTSOH) data when over a remote controlled telemetry tracking station in Fairbanks, Alaska. At 2000, 3000, and 4000 seconds after separation the non-essential bus was enabled, the command and telemetry unit (CTU) downlink module was turned on followed by the UHF transmitter. Ninety minutes after launch the satellite's UHF signal was picked up at the Fairbanks tracking station and data was routed to the Albuquerque ground station. This first data confirmed the launch and separation timer actions had performed flawlessly. The satellite's arrays were deployed and facing the sun, the battery was fully charged, and the telemetry system was transmitting data.

Nine and a half hours after launch, the satellite came in view of the Albuquerque DOE experimental ground station, and the preprogrammed pass procedure was executed flawlessly. This confirmed command capability was established and enabled a full check and verification of satellite telemetry. Over the next few days, preprogrammed procedures were executed that sequenced on various satellite components until all subsystems were operating.

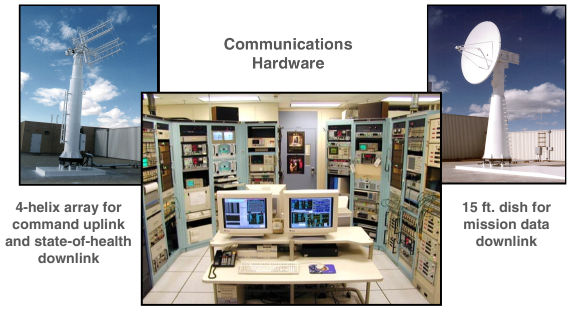

Figure 4 DOE experimental ground station

Early on-orbit imaging check out

The first MTI image was collected by simply opening the payload telescope aperture door at a pre-determined time, collecting 5000 frames of data from the focal plane array and then closing the door. This produced an image of the Lake Erie coastline in Ohio. At the time, the satellite was in its nominal sun pointing attitude. Comparison of this to the calculated projection of the telescope field-of-view (FOV) confirmed that the telescope to the attitude determination and control subsystem alignment was within expected tolerances.

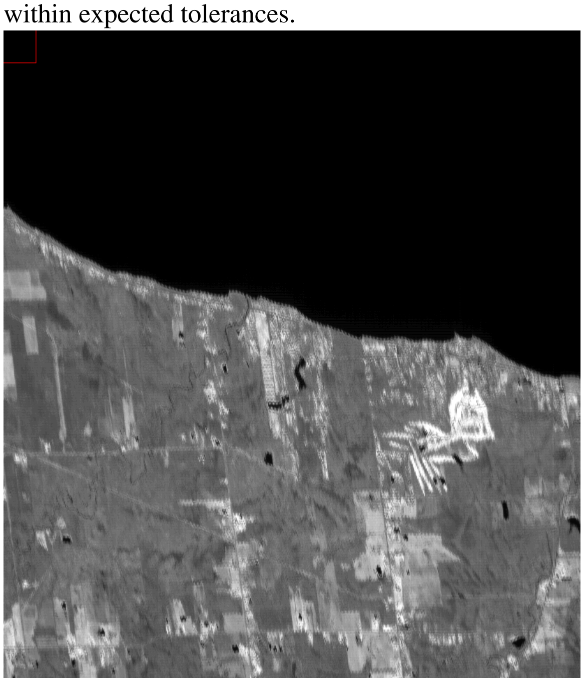

Figure 5 Portion of first image collected

The next set of operations performed during early orbit check maneuvered the satellite's attitude about the sun vector in each of the satellite's orthogonal axis (pitch, roll, and yaw), while collecting data from the fine sun sensor and the IRU. This data was processed to determine the alignment of the IRU to the attitude solution using the sun and earth vectors.

The imaging timeline for MTI uses the earth and sun vectors at optimal points in the orbit to calculate an absolute attitude solution in inertial space. The attitude determination subsystem then uses IRU data to propagate the attitude solution forward in time. This allows a very precise attitude solution for any location in the satellite's orbit including eclipse periods where the sun and sometime even earth vectors are undeterminable. It also provides a precise attitude solution during high angular rate maneuvers required to record two images of a given site during the same pass.

After the alignment of the IRU to the attitude solution had been determined, the operations team was able to calculate a control frame needed to appropriately point the telescope FOV such that the focal plane's linear arrays sweep across the target while data is being clocked out. During imaging, a constant angular rate is maintained by the satellite.

In addition to the alignment procedures briefly described above, early on-orbit checks included rigorous payload turn-on and calibration procedures. This included collection of focal plane data while viewing internal calibration sources and cold space with focal plane temperatures set at 90, 85, 80 and 75 Kelvin (the nominal operating temperature). Readers are referred to references 1 and 3 for details on imaging performance.

Pointing performance has proved very accurate as illustrated by images of Washington DC taken on three consecutive days (see figure 6). The satellite was designed to a pointing requirement of ±5.0 km (2.3 sigma); however, actual performance has been shown to be better than ±2.0 km. The pointing budget includes a number of factors. The onboard GPS receiver provides the satellite with accurate position, time, and velocity. The fine sun sensor and horizon scanner provide accurate sun and earth

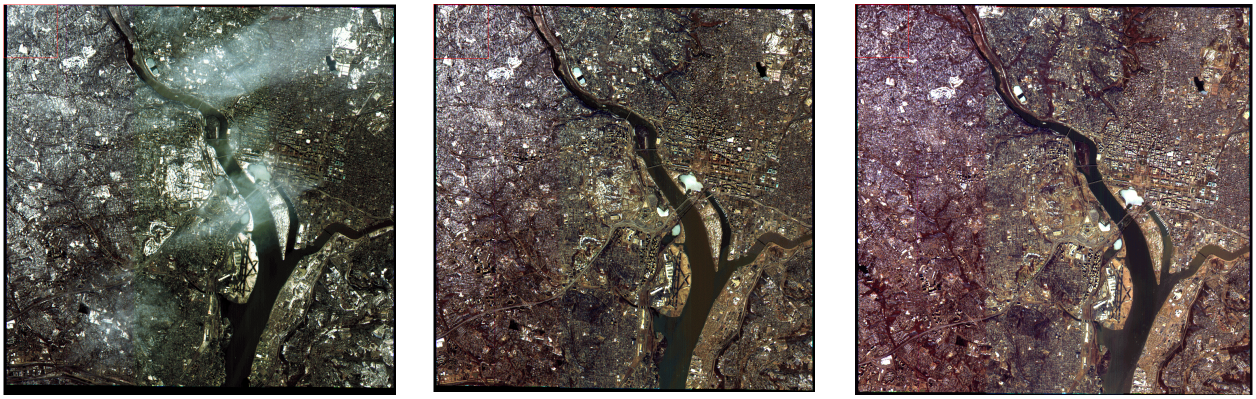

Figure 6 Sequence of images over Washington DC

vectors. The control bandwidth of the attitude actuators also effect the pointing accuracy of the satellite.

Current Status

The MTI satellite was pronounced ready to commence its R&D mission June 14, 2000. At the time of this writing, MTI has collected data of instrumented ground sites for just over a year. During this time, it has collected over 1850, 2-look image sequences, and it is currently collecting over six image sequences per day. Of the 381 days the satellite has been supporting its R&D mission, it has been available 354 days or 93% of the time, which is well over the 80% system performance goal. A summary of images collected to date is listed in the following table:

	# of images	%
DOE core sites	836	44.4
DOE other	192	10.2
MTI User Group	601	31.9
Other	253	13.4
Total	1882	100.0

Table 2 Image Summary

Each image sequence generates about 50 Megabytes of compressed data from the MTI satellite. A typical compression ratio achieved onboard the satellite using the Rice compression algorithm is 2.8:1. Compressed data is sent to the MTI Data Processing

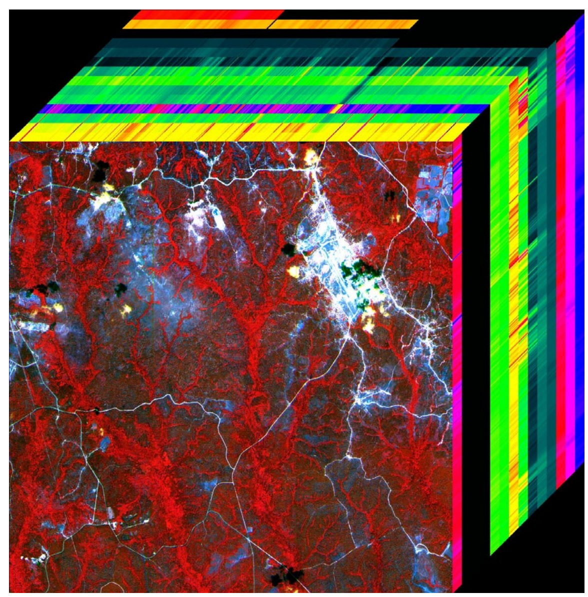

Figure 7 MTI image cube

and Analysis Center in Los Alamos, where it is decompressed, calibration coefficients are applied, and processed to produce a two dimensional image for each of the different 15 spectral bands. Image cubes, like the one shown in Figure 7, are sent to the experimenters on compact disks. An image sequence processed by the DPAC contains 1.17 Gigabytes of

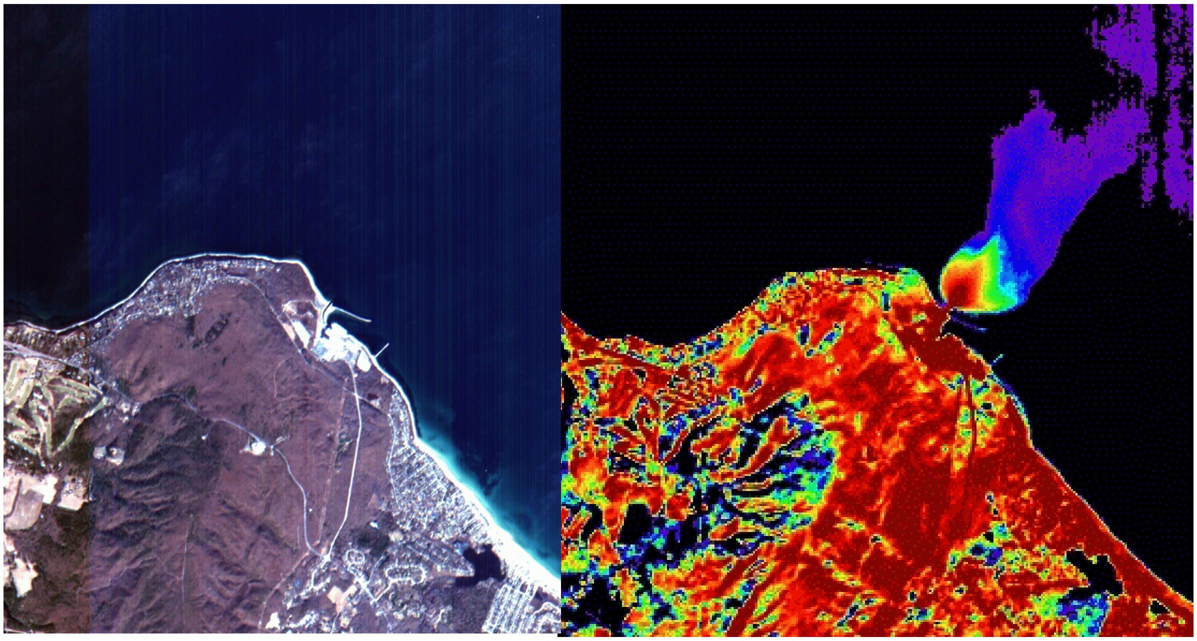

Figure 8 Thermal image compared to true color image

data. Over 2.2 Terabytes of data have been produced by the MTI project team since launch. To date the project has collected a sufficient number of images and simultaneous ground truth data to evaluate whether or not performance objectives were achieved and to evaluate the technology's treaty monitoring utility. Figure 8 demonstrates the systems multispectral thermal utility. This figure shows a true color image compared with a thermal image of the same area. The thermal image was collected with band N at ~10 microns. Studies are underway to determine the absolute accuracy of the thermal measurements.

Summary and Conclusions

In summary, the project had a successful launch and on-orbit checkout. Pointing and alignment performance is well within specifications, and MTI continues to produce imagery for a broad range of R&D experiments with a 93% availability rate. The project has validated key component designs and performance goals. Although data analyses are not yet complete, there is good reason to believe the project achieved instrument spatial, radiometric and other performance goals. The satellite has also collected a large amount of data in support of other military and civilian R&D.

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